Determining reflectivity measurement error from serial measurements using paired disdrometers and profilers

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[1] Serial reflectivity measurements from paired instruments are examined during two field campaigns in order to examine the *precision* of the measurements. The instruments studied are two collocated Joss-Waldvogel disdrometers (JWD) at Wallops Island, VA and two collocated profilers deployed at Ji-Parana, Brazil during Tropical Rainfall Measuring Mission (TRMM) Large-Scale Biosphere-Atmosphere Experiment. Differencing the measured reflectivity from the instrument pairs eliminated most of the temporal and large-scale precipitation variability, reducing the error fluctuations to those of the instrument *precision* plus fluctuations due to precipitation variability over the small differences in sample volume and distances between the instruments. For both pairs of calibrated instruments we found that the observed time-series of one-minute dBZ differences were not autocorrelated and exhibited a Gaussian-like distribution. Consequently, the difference time-series could be meaningfully characterized by their standard statistics, including the rms difference or standard deviation, and the standard error about the mean. While the disdrometer pair exhibited an rms difference of 2.1 dBZ, a standard error about the mean of less than 0.1 dBZ for the 12-hour rain event was achieved. The profiler pair exhibited an rms difference of 0.4 dBZ, with a standard error of only 0.05 dBZ for the 90-minute stratiform rain event. Since it is currently difficult to routinely calibrate radars in an absolute sense to better than 1–3 dBZ, the precisions of a few tenths of a dBZ obtained here suggest the potential for substantially improving these calibrations, and open the door to examination of subtle sampling and stability effects. *INDEX TERMS:* 0910 Exploration Geophysics: Data processing; 0634 Electromagnetics: Measurement and standards; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; 6994 Radio Science: Instruments and techniques. **Citation:** Gage, K. S., W. L. Clark, C. R. Williams, and A. Tokay (2004), Determining reflectivity measurement error from serial measurements using paired disdrometers and profilers, *Geophys. Res. Lett.*, *31*, L23107, doi:10.1029/2004GL020591.

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1. Introduction

[2] Accurate precipitation measurements are of critical importance to the determination of the hydrologic cycle and are needed for validation of models (including climate, hydrologic and cloud-scale models). Ground-based radar is an important tool for calibration and validation of precipitation estimates from satellites such as the Tropical Rainfall Measuring Mission (TRMM) satellite. For validation it is important to have good estimates of the error characteristics of observed precipitation parameters. Indeed, the error characteristics are essential for optimal data assimilation [*Daley*, 1997]. As a step toward this goal, this paper focuses on quantification of the reflectivity measurement error attainable by two commonly used instruments for precipitation research and ground validation of satellite estimates of precipitation.

[3] In general it is not possible to quantify measurement error *in an absolute sense* unless a reference is available to provide the *true* value of the quantity that is being measured. However, the precision of a particular type of instrument can be explored by comparing measurements of the same quantity across an ensemble of the instruments. In this paper we compare a pair of impact disdrometers and a pair of precipitation profilers, and find that both instruments can characterize an extended time series of rain observations with an exceedingly *precise* mean value of reflectivity (dBZ).

2. Instruments and Methods

[4] For precipitation measurement a fundamental attribute is the distribution of hydrometeors of different sizes within the observation volume. In the case of rain the drop-size distribution, N(D), where the drop diameter D is the fundamental parameter, may be determined in situ by a disdrometer sampling a near-surface volume defined by the fall speed of the drops, the temporal resolution of the disdrometer (typically, one minute), and the cross section of the disdrometer. N(D) is highly variable in time and space during rain events but is more homogeneous in stratiform rain than convective rain.

[5] For radar measurement in rain the reflectivity factor Z ($mm^6\ m^{-3}$) is a fundamental quantity [*Rogers and Yau*, 1989]. The reflectivity factor is related to the drop-size

Figure 1. Two precipitation profilers operated during TRMM LBA in January and February 1999 at the Ji Parana Municipal airport in the Rodonia Province of Brazil. The shrouds for the 915 MHz profiler and 2835 MHz profiler antennas can be seen in the background. A Joss-Waldvogel disdrometer is visible on the tripod in the foreground.

distribution by $Z \equiv \int N(D)D^6\, dD$. Since Z varies over many orders of magnitude, it is common practice to give Z in units of dBZ ($\equiv$ 10 log Z). This transformation is useful for calibration work, since dBZ observational differences between the instruments have a near normal distribution. For the purposes of this paper we regard the factory calibration of the JWD disdrometers, which is based on measuring the response of the instruments to the impact of calibrated drops, as sufficiently accurate to make a JWD disdrometer a useable reference standard. Instead, the focus of this paper is to show that it is possible to achieve sufficient *precision* from a series of observations (both disdrometer and profiler) to make use of this *accuracy*. As suggested above, this study is accomplished by having two collocated disdrometers and, in a separate study, two collocated profilers observe a precipitation event simultaneously. The time series of the one-minute differences (in dBZ space) between these observations is then used to quantify measurement error.

[6] The JWD [*Joss and Waldvogel*, 1967; *Tokay et al.*, 2001] is an impact disdrometer that produces a voltage waveform when a drop strikes the surface of its 50 square centimeter Styrofoam cone. The waveform amplitude is calibrated to provide a measurement of the momentum transfer of the drops, which is directly related to their size. The JWD has a dead time immediately following the impact of a drop and in heavy rain this can lead to undercounting of raindrops but the effect is apparently not significant [e.g., *Sheppard and Joe*, 1994]. It is assumed that the momentum is entirely due to hydrometeor terminal fall velocities in still air assuming drops are spherical.

[7] UHF and S-band precipitation profilers developed at the NOAA Aeronomy Laboratory [*Ecklund et al.*, 1999; *Gage et al.*, 2003] are used in this study to measure reflectivity remotely. During the TRMM Ground Validation field campaigns the precipitation profilers were utilized as part of a multi-sensor suite of ground-based instruments for calibration and validation of scanning radars [*Gage et al.*, 2002].

[8] The collocated profilers used in this study are shown in Figure 1 as deployed at the Ji Parana Airport during the TRMM LBA campaign conducted in Brazil in early 1999. The profilers were vertically directed and transmitted at 915 MHz and 2835 MHz respectively. Every minute a simultaneous 30-second observation of reflectivity was recorded from each of these profilers, and it is the dBZ difference of these observations that is used here. Although these results represent only a short case study, we believe they illustrate the principles involved and provide typical estimates of the *precision* of the instruments used. A JWD may also be seen on a tripod in the foreground. It was used to calibrate the profiler reflectivities for the LBA campaign and is the same type of instrument as those used in the Wallops Island experiment to be described next.

3. Analysis of Reflectivity From Paired Disdrometers

[9] The top panel of Figure 2 shows time series of reflectivities calculated from the two collocated JWDs at Wallops Island on March 21, 2001. This rain event was 12 hours long commencing just after midnight. The mean rain rate was 4.3 mmhr^{-1} while the maximum rate was

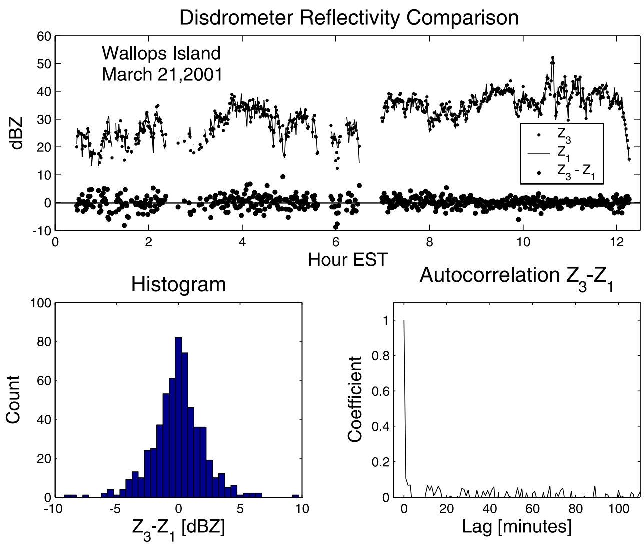

Figure 2. Reflectivity calculated from two collocated Joss-Waldvogel disdrometers located at Wallops Island, Virginia on March 21, 2001. Top Panel: Overlaid time series of Z as observed with each JWD. The observations from JWD_1 are plotted with a line, those from JWD_3 with small dots. Below the overlaid time series large dots plot the time series of observation differences $Z_3 - Z_1$. Two lines indicating the 95% confidence interval about the bias are also shown, but are so closely spaced they appear as one line. Bottom Left Panel: The histogram of $Z_3 - Z_1$. Bottom Right Panel: The autocorrelation of $Z_3 - Z_1$ for 1 minute lags from 0 to 110 minutes. The subscripts identify the disdrometers within a larger array at Wallops Island site.

86 mmhr^{-1}. Individual values are for each minute and the disdrometers were spaced about 1 meter apart. Note the two disdrometers show similar traces of reflectivity, which can be seen to be highly variable, yet highly correlated. The time series of reflectivity differences are shown just below the overlaid time series. The Gaussian looking histogram and the lack of autocorrelation shown in the bottom panels of Figure 2 strongly suggest that the differences are independent of each other. This is to be expected if the differencing process has dampened the larger scale correlations sufficiently that sampling and instrument error dominate the results. Although the distribution shown in the histogram does not pass a Lilliefors test for normality [*Davis*, 1986, p. 101] at the 5% level, the halves of the series divided at 0645 EST do pass the test. This appears to be because the first half exhibits an instrument difference variance nearly three times larger than the second half. This difference in variance probably reflects improvement of the sampling precision of the disdrometer due to the higher rain rates occurring over the second half of the event, as evidenced in Figure 2 by the consistently higher reflectivities seen after 0645 EST. A statistical analysis of the difference data contained in Figure 2 yielded a standard error of about 0.09 dBZ and a standard deviation and root mean square difference of about 2.07 dBZ.

[10] Summarizing, we can say that the *precision* of an individual one minute difference as represented by the standard deviation was a rather broad 2.1 dBZ, but, and most importantly, the standard error of the mean difference over the entire twelve hour period was less than 0.1 dBZ.

4. Analysis of the Reflectivity From Paired Profilers

[11] For the TRMM Field Campaigns the NOAA Aeronomy Laboratory deployed a pair of vertically looking profilers in order to reveal the vertical structure of the precipitating cloud systems as they advect over the profilers and to develop a methodology to retrieve drop-size distributions from the profiler observations. Vertically pointing Doppler radars had been used previously [e.g., *Atlas et al.*, 1973] to examine the structure of precipitating cloud systems but modern profilers are configured in a way that makes them ideal tools for this purpose [*Rogers et al.*, 1993; *Gage et al.*, 1994].

[12] The 2835 MHz precipitation profiler was developed especially for TRMM to provide a sensitive low-powered instrument with relatively little sensitivity to Bragg scatter that could profile precipitation parameters [*Gage et al.*, 2003]. Nonetheless, the 2835 MHz system is similar to the low-powered 915 MHz profiler collocated at the site, and both use an identical control system developed in house for the 915 MHz profiler [*Carter et al.*, 1995]. The vertically pointing fixed antennas used in each system were selected so that both profilers sample nearly the same volume. The configurations of the two profilers were matched and the sampling synchronized to observe simultaneously using a nominal 100-meter pulse length. These matched soundings occurred during the first 30 seconds of each minute, while unmatched soundings not considered here took up the latter half. Each sounding is independent of the last, since drops completely fall through the 100 m range gate in the 60 seconds between soundings. The instruments and the field campaign are described in more detail in *Gage et al.* [2002].

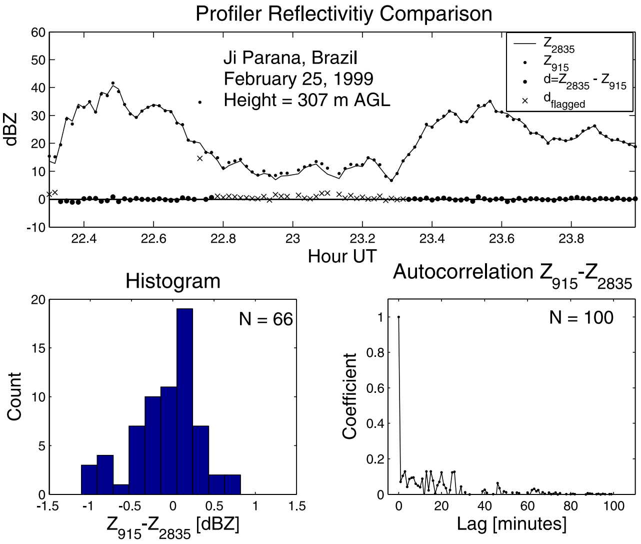

Figure 3. As in Figure 2 except for a pair of precipitation profilers located at Ji Parana, Brazil on February 25, 1999, during TRMM LBA. The line represents Z values from the 2835 MHz profiler, the dots from the 915 MHz system. The x symbols on the difference plot represent data rejected from the analysis, most often because Z was observed below the 15-dBZ threshold used to reduce the significance of clear air enhancement in the 915 MHz signal, but also in one case because the difference observation was more than 3 sigma from the mean difference. The bottom panels again show the histogram of the unflagged difference time series values and the autocorrelation of all the values.

[13] Profiler reflectivities are obtained directly from the zeroth moment of the Doppler power spectrum measured by the vertically pointing profiler. A sample of profiler reflectivities from TRMM LBA is shown in Figure 3. This particular example illustrates stratiform precipitation. The individual samples plotted are reflectivities for each 30-second sample of the two profilers. Unlike the disdrometer, which samples a small volume near the surface, the profiler samples a much larger volume formed by the range gate and the conical vertically looking beam. The lowest fully recovered range gate was centered at 307 meters and provided the observations in Figure 3. The temporal variability for the reflectivity time series for the two instruments is obviously highly correlated.

[14] Note that there is a systematic reflectivity difference evident between the two profilers at low reflectivities. This can best be seen from 22.8 to 23.2 hours. This systematic difference is due to the presence of Bragg scatter from turbulent inhomogeneities in radio refractive index that gives profilers their ability to observe in clear air. Relative to scatter from hydrometeors the 915 MHz profiler is more sensitive than the 2835 MHz profiler to Bragg scatter, as detailed, for example, by *Gage et al.* [1999]. This contamination due to Bragg scatter can be avoided by not considering low reflectivities (in this study we required Z > 15 dBZ) or, somewhat equivalently, by requiring a minimum threshold of drops in the disdrometer sample. The

elimination of disdrometer samples with a small number of drops also alleviates the sampling bias described in the simulation study by *Smith et al.* [1993].

[15] As in the disdrometer comparison, we see in the bottom panels of Figure 3 a Gaussian like histogram depicting the observed distribution which passes the Lilliefors normality test at the 5% level and an autocorrelation plot showing negligible correlation beyond 0 lag. The statistical analysis of the difference time series yielded a standard error of about 0.051 dBZ and a standard deviation and root mean square difference of about 0.4 dBZ.

5. Discussion

[16] In this paper we have examined serial measurements of paired instruments in order to gain insight into the reflectivity measurement error of the instruments. We have demonstrated that this approach can be utilized to determine error characteristics of the instruments involved even though the measured quantities possess substantial temporal and spatial variability. The utility of this methodology for calibration of radar is directly related to the ability of the instruments to repeatedly observe the same quantity. With respect to precipitation, even instruments that are observing somewhat different but closely related volumes may satisfy this criterion, provided the event is sufficiently homogeneous locally (C. R. Williams et al., Monitoring the reflectivity calibration of a scanning radar using a profiling radar and a disdrometer, submitted to *Journal of Atmospheric and Oceanic Technology*, 2004). Of course, the effect of spatial variability is minimal in this study where the paired disdrometers were one meter apart, and the profilers sampled nearly identical volumes, but must be considered when, for example, using disdrometers to calibrate a profiler by comparison with a profiler sampling volume a pulse length or so above the disdrometer, or when using profilers to calibrate a scanning radar where pulse volumes may not closely match.

[17] Use of the methodology developed here for actual calibrations depends on the accuracy of the absolute calibration of the disdrometer, since it is used as the transfer standard. We believe that the factory calibration of JWDs is quite stable, as demonstrated in an extensive side-by-side comparison of multiple disdrometers carried out at Wallops Island by A. Tokay et al. (Error characteristics of rainfall measurements by collocated Joss-Waldvogel disdrometers, submitted to *Journal of Atmospheric and Oceanic Technology*, 2004, hereinafter referred to as Tokay et al., submitted manuscript, 2004). Nevertheless, it should be kept in mind that these same authors found differences in an absolute sense of ±0.5 dBZ across their 1.4×3.8 m ensemble of disdrometers. Furthermore, Tokay et al. (submitted manuscript, 2004) have shown that a well-calibrated JWD may show storm-to-storm variation of ±0.2 dBZ in bias relative to the mean value of the ensemble. However, the same study showed that the RMS differences between pairs of collocated disdrometers were fairly consistent implying that the *precision* of these instruments is stable. These findings suggest that the disdrometer itself limits the *accuracy* of calibration to about ±0.5 dBZ even though repeated measurements can be much more *precise*. Indeed, we cannot rule out the possibility of systematic errors that can arise from instrument bias that is inherent to the instrument design. Our experience, however, indicates that the *precision* of the disdrometer and the profiler time-matched mean reflectivity factors are very high and that both instruments behave in a stable and robust manner that makes possible their use unattended over extended periods of time.

6. Conclusion

[18] The comparisons presented in this paper serve to roughly quantify the measurement error that can be obtained from Joss-Waldvogel disdrometers and radar precipitation profilers in characterizing a set of precipitation observations with a mean value of reflectivity, Z (dBZ). Z in these case studies represents 1-minute reflectivity observations. Only short case studies are presented here, so the results are representative, not definitive. However, the results suggest that the mean reflectivity characterizing an extended set of rain observations may be determined with *precisions* of the order of 0.1 dBZ, and the *precision* improves with sample size. In other words, we found that the instrument pairs used in these case studies measured the same mean value of Z to better than 0.1 dBZ. This *precision* is as good or better than most engineering calibrations of absolute radar reflectivity, and supports the use of absolutely calibrated disdrometers to create "standard targets" out of rain events that are observed simultaneously by collocated disdrometer-profiler systems. In this situation, removal of the bias in observed mean Z between the two instruments constitutes a reflectivity calibration of the profiler. As a side benefit, the *precision* of such comparisons should allow examination of small systematic biases that may be inherent in either instrument, such as saturation of the radar, or dead- time for the disdrometer.

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